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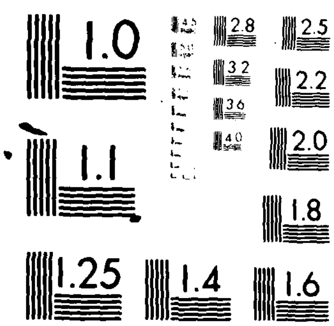
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STUDY OF GEOMAGNETIC STORMS, SOLAR FLARES, AND CENTERS OF ACTIVITY IN 1976, THE YEAR BETWEEN SOLAR ACTIVITY CYCLES 20 AND 21

E. Ruth Hedeman
Helen Dodson Prince

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20810

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Solar and geophysical circumstances prior to the 34 principal geomagnetic storms in 1976 have been evaluated. In this year of sun spot minima, 21 of the storms were unambiguously classified as sequential. For 7 of the storms prior flares may have played a role. Six of the storms remain as "problem" situations. The 3 most severe storms in 1976 were associated with the 3 flares in 1976 with Comprehensive Flare Indices $\geq$ 10.

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Inspection of plots of daily geomagnetic character figures suggest that at least 6 different sequences contributed to the geomagnetic disturbance in 1976. Relationships were sought between inferred coronal holes and the observed locations of significant centers of activity as the possible origins of the sequential storm particles. All of the major recurrent storm sequences in 1976 apparently had at their roots significant centers of activity that could have been near the perimeters of deduced associated coronal holes. The sequential storms occurred as the active regions were dying and continued long after all optical events of the active regions had disappeared.

I. INTRODUCTION

Prior work in the program of comparisons between observed solar phenomena and certain geophysical effects has included studies of geomagnetic storms in the seven years of increasing and maximum solar activity, 1955-1957 and 1965-1968. The present study attempts to review the relationships between solar phenomena and geomagnetic storms in 1976, a very different time in the solar cycle, the year of minimum activity between solar cycles 20 and 21.

The study seemed of especial interest because the 1976 minimum was a rather special minimum. It was the minimum with the *highest* level of *residual* activity since 1755, the date after which sun spot numbers have been known with considerable accuracy. (See Table 1.) The smallest value of smoothed monthly sun spot relative number in 1976 was 12.2 in both March and June. In many minima the corresponding values of residual sun spot activity have been 5.0 or less, and the only close competitors for high residual values were 11.2 in 1766 and 10.5 in 1843. (See Table 1.)

Although 1976 was the year of minimum between cycles 20 and 21, there were intervals of enhanced solar activity in the spring of '76 that led to a ground-level enhancement of cosmic rays and a small increase or "stillstande" in the plot of mean monthly sunspot numbers for cycle 20. (See Figure 1.) It was a year with a *mixture* of solar activity and solar calm and seems to be an interval worthy of special examination. Additionally, 1976 was a year with its first half dominated by old cycle centers of activity and its second half by new cycle features. During the second half of the year, new cycle spots and regions spread rapidly to all longitudes and the mean latitudes decreased markedly from very high (30°-45°) to lower values (15°-20°).

Geomagnetically, 1976 was dominated by "sequential", or approximately 27-day recurrent storms, that are characteristic of minimum and the years of declining activity in the solar cycle. There were, however, a few so-called "sporadic" or non-sequential disturbances. In addition, there were certain storms that were borderline cases for both of these categories. In recent years, there has been great progress in the association of sequential storms with solar wind streams emanating from long lasting "coronal holes" with their weak coronal emission and open magnetic field lines. Sporadic storms, on the other hand, are generally thought to be flare-associated.

For this study, all geomagnetic storms reported in 1976 by the world-wide network of geomagnetic stations have been evaluated on the basis of the severity and duration of the geomagnetic disturbance. For purposes of comparison, storms with maximum values of the 3-hourly Kp as great as 7, 8, and 9 have been considered as "severe". Storms with maximum Kp of 5 and 6 have been classified as "moderate". Weaker disturbances with maximum Kp of only 4 or less have been omitted from the survey. Solar records and reports have been searched in efforts to recognize the solar phenomena apparently responsible for each storm in 1976 for which the 3-hourly Kp became as great as 5.

II. PROCEDURE

A. Derivation of Comprehensive Flare Index (CFI)

To assist in the evaluation of the relationships between flares and geophysical effects, a Comprehensive Flare Index (CFI) based on the radio frequency and ionizing radiation of a flare as well as on its optical importance was developed by *Dodson and Hedeman (1971)*. The index is determined by five components which, when taken sequentially, constitute a crude profile of the electromagnetic radiation of the flare. The *sum* of the five components gives the Comprehensive Flare Index. The five quantities that comprise the flare profile and the Comprehensive Index are as follows:

1. Importance of ionizing radiation as indicated by time-associated Short Wave Fade or Sudden Ionospheric Disturbance; (scale 0-3)

   Note: Direct measurement of X-ray flux, if available, would be preferable to this indirect indication of its magnitude. The correlation, however, between SWF importance and X-ray flux appears to be gratifyingly close. (*Dodson and Hedeman*, UAG Report 52, 1975).

2. Importance of Hα flare (scale 0-3)

3. Magnitude of ~ 10 cm flux (characteristic of log of flux in units of 10^{-22} Wm^{-2} $(C/S)^{-1}$).

4. Dynamic spectrum (scale 0-3; Type II = 1, Continuum = 2, Type IV with duration > 10 min. = 3)

5. Magnitude of ~ 200 MHz flux (characteristic of log of flux in units of 10^{-22} Wm^{-2} $(C/S)^{-1}$).

The Comprehensive Flare Index can be determined for any flare for which the needed observations exist. Values of the Index have been derived and *published (Dodson and Hedeman, 1971; 1975)* for all flares in the years

1955-1974 that could be considered as "major" on the basis of any *one* of the following criteria:

Shortwave fade or SID, importance ≥ 3

$H\alpha$ flare, importance ≥ 3

10 cm flux $\geq 500 \times 10^{-22} Wm^{-2} (C/S)^{-1}$

Type II burst

Type IV radio emission, duration > 10 minutes

The Comprehensive Indices for all "major" flares in the later years, 1975 to mid 1978, also have been determined but are not published. Table 2 of this report provides data on the Comprehensive Flare Index for all "major" flares in 1976. It seems of some interest that in 1976, the year of solar minimum there were 31 events that qualified as "major" flares. Included in the list were three flares for which the CFI was ≥ 10 (see Table 2). These great flares took place on March 23, March 28, and April 30, 1976 all within the same plage family. A ground level cosmic ray enhancement (GLE) occurred in time association with the April 30th flare.

B. Statitical Relationships Between "Major" Flares and Geomagnetic Disturbance

If one pays no attention to time relationships one can say, but without any significance, that all geomagnetic storms have been preceded by flares. Conversely one can say that all flares are followed by geomagnetic storm, if one accepts any time interval between the two events no matter how long or short. Obviously efforts to ascribe specific geomagnetic storms to specific flares must be guided by the actually observed relationships between flares and geomagnetic disturbance. To this end, we refer to the statistical relationships previously reported in this project between "major" flares and geomagnetic disturbance. In this program, mean values were derived for superposed daily Σ Kp geomagnetic indices for 6 days before and 6 days after the occurrence of all "major" flares (as defined above) for the years 1957-1963 and 1966-1969. For this study, the major flares were divided into three groups based on values of the Comprehensive Flare Index, viz. > 10, 6-10, < 6.

According to this investigation, for the years studied in both cycles 19 and 20, the relationships between flares in the different categories were, in general, both definite and consistent. For "major" flares with Comprehensive

Flare Indices > 10, there was a well defined, relatively large increase in the mean values of Σ Kp indices on days 1, 2, and 3 following the day of flare occurrence. For "major" flares with values of the Comprehensive Index 6-10, there was only a small rise, or none, in the mean values of Σ Kp on the days following the flares. However, for even "major" flares with Comprehensive Indices < 6, the mean values of Σ Kp did not increase. These results indicated a clear statistical association between geomagnetic disturbance and the truly great flares with strong ionizing and radio frequency emission, but deny such associations for flares without these characteristics. The work suggested that assignment of geomagnetic storm-causation to minor or only average flares is seldom justified. It is through application of the above results that in the present study we have made certain definite flare and storm associations, or more often made the comment "no suitable or appropriate prior flare".

III. STUDY OF THE 34 PRINCIPAL GEOMAGNETIC STORMS IN 1976

A. Classification and Severity

With the foregoing statistical studies for guidance, an attempt has been made to evaluate solar circumstances prior to each of the 34 principal geomagnetic storms in 1976. All storms for which the 3-hourly Kp became as great as 5 have been considered in the investigation. Geomagnetic disturbances with maximum 3-hourly Kp of only 4 have been omitted. The time covered by the study includes the time of minimum in solar activity between solar cycles 20 and 21.

In this work, we have recognized three principal categories of storms, viz. flare-associated, sequential, and "problem". We have considered as flare-associated, those storms that were preceded within the prior 16 to 84 hours by flare events that were, in our judgement, above average in either Hα, ionizing, or radio frequency emission. Storms without apparently suitable prior flares but which occurred in approximately 27 to 29 day recurrence patterns have been classified as sequential. The designation "sequential" is based on simple examination of plots of C_Q and Kp geomagnetic indices and the recognition of approximately 27 to 29 day recurrence patterns in the geomagnetic data. The "problem" storms are the non-sequential disturbances for which seemingly appropriate prior flares were not observed. In addition, we sometimes felt obliged to indicate that certain storms could be either flare associated or sequential. In such cases, we have used the double term

"flare-sequential" or "sequential-flare" to point out the uncertainty. The first member of the double term represents our best judgement in each case.

Summaries of the data relating to our evaluations of the 34 principal geomagnetic storms in 1976 are given in Tables 3A and B, of this report. In 1976, 21 of the 34 storms were unambiguously classified as sequential. In the year of the prior minimum (1964) there had been 22 sequential storms. In 1976, 2 storms were unambiguously flare associated, 2 storms were classified as flare-sequential and 3 as sequential-flare. Thus, for 7 of the 34 storms in 1976, flares may have played a role. Six of the storms in 1976 remain as "problem" situations. (See Table 4.)

A chronological list of the geomagnetic storms in 1976 with their classification and rank is given in Table 5. An asterisk has been introduced after the classification of the storm if it was time-associated with a sector boundary passage. This was the case for 15, primarily sequential, storms in 1976. (See Tables 3 and 5). We have not had access to coronal hole data for 1976 (except for October and December) but one might expect that the sequential storms in 1976 followed the central meridian transit of coronal holes.

B. Flare-Associated Storms in 1976

In 1976, there were no storms with maximum 3-hr. Kp as great as 9, but there were 3 storms with *maximum values as great as* 8. These three most severe storms in 1976 were all flare-associated. The most severe storm, that of March 26, was also sequential. This storm is associated with the flare-event on March 23 with the highest value of the Comprehensive Flare Index observed in 1976 (CFI = 12). It was only a sub-flare optically but it was outstanding in ionizing and radio frequency emission (see Table 2). Its location at E90° suggests that it probably was a truly great flare but a bit behind the east limb. It marked the beginning of the transit of McMath-Plage 14,143 which was the site of 8 "major" flares during its disk transit. The second most severe storm of 1976, that of April 1, is also attributed to flares in this region. The storm 3rd in severity in 1976 (May 2) also is associated with this center of activity in its *next* rotation (designated Plage 14179). This region, when at W45°, produced on April 30 a flare with CFI of 11 accompanied by a ground level enhancement of cosmic rays. There were only three flares in 1976 with Comprehensive Flare Indices ≥ 10. They were all in this same center of activity and its return. They were the apparent source of storm particles for the three most severe storms of the year. They

were the only storms in 1976 in which max 3-hr. Kp was as great as 8. The region Plage 14143, CMP March 31, S07°, included a γ-type spot and had an Active Region Index of 12. It would be considered a truly great center of activity at any time in the solar cycle. As stated before, it developed 8 "major" flares in its March transit, and it was associated with 29 ionospheric disturbances. It seems appropriate that the three greatest geomagnetic disturbances of the year 1976 were associated with phenomena in this great center of activity in its March and April transits. It is a bit surprising, however, to have had the occurrence of such a truly great center of activity so very close to the time of statistical minimum in the 13 month running means of sun spot numbers (March and June, 1976) - but that is what happened during the minimum between cycles 20 and 21.

C. The Sequential Storms and Their Possible Relationship to the Principal Centers of Activity in 1976

Inspection of plots of the C_9 daily geomagnetic character figures, suggests that at least six different sequences contributed to the geomagnetic disturbances in 1976. These sequences are shown schematically in Figure 2. The six sequences are indicated by numbers in parentheses. Five of the sequences show a 27 day recurrence pattern but sequence 6, with its series of rather weak storms, appears as a 29 day recurrence phenomenon. We assume that coronal holes were associated with these sequences and are curious as to whether there was an identifiable source of the solar particles that eventually left the sun over the open field lines of the coronal hole. Let us take the sequences as the argument of entry into the data and see if significant centers of activity were in the neighborhood of the assumed coronal holes and could have served as the sources from which the sequential storm particles originated. In Figure 2, the centers of activity are shown by circles.

Sequence No. 1: This sequence begins around the 14th of August in 1975 and lasts until at least March of 1976. It seems of some interest that the greatest center of activity in 1975, (Plage 13790), N09, Active Region Index of 11, crossed the central meridian on August 9, 1975, just four or five days before the feeble start of the sequence. Was this important region colongitudinal with the sequence-associated coronal hole and did it in some way provide the particles of sequence one? It should be noted that the sequence was weak during the rotations (1631 and 1632) in which the active region was great, but becomes strong and well defined in subsequent rotations

when the region is diminishing or has disappeared entirely from optical records. The sequence lasts for at least nine rotations. If it is related to active region 13790, it is primarily a phenomenon of the dying and very late phase of the region and not of the time of its greatest activity. However, another active region was located in the same longitude but in southern latitudes (Plage 14029, CMP January 18, 1976, Rotation 1637, S13°, ARI = 5) and may have continued to provide particles for the later members of this sequential solar wind stream. See discussion for Sequence no. 5.

Sequence No. 2: This sequence that begins around November 10, 1975 (Rotation 1634) and lasts for perhaps ten rotations is well developed in January, February, and March of 1976. Again, it is of some interest that another of the ten most active regions in 1975, Plage 13926, N06, ARI =2, crossed the central meridian on November 11, 1975. Was this region on the following edge of a coronal hole associated with Sequence 2? Again, the sequence has its principal development a number of rotations *after* the most active phase of the possibly associated active region.

Sequence No. 3: This poorly defined sequence in 1976 is preceded by a sequence of weak storms that began on October 3, 1975, (Rotation 1633). Active Regions preceding this sequential storm pattern in 1975 were Plages 13786, CMP Aug 5 (Rotation 1631) latitude N05, AR1 = 9 and Plage 13937, S07, CMP Nov 7, (Rotation 1635) AR1 = 8 and were colongitudinal with the coronal hole assumed to be associated with the sequence. Did these centers of activity provide the particles that left the sun through the open field lines of the coronal hole?

Sequence No. 4: This sequence, that begins on January 10, 1976 (Rotation 1636) develops two rotations after the November 20, 1975 meridian passage of Plage 13937, S07, AR1 = 8, mentioned above. Did a coronal hole develop on preceding as well as the following edge of this active region as the region dies? It should be noted that Sequences 3 and 4 appear to merge after February 1976.

Sequence No. 5: Sequence No. 5 that begins on June 3, 1976 (Rotation 1642) could be a resurgence of Sequence No. 1 for which we assumed a preceding coronal hole. A coronal hole actually was observed preceding Sequence No. 5 in October and December 1976. Is this a continuation of the same coronal hole that was assumed earlier? As mentioned at the end of the discussion for Sequence No. 1, Plage 14029 (Rotation 1637) may have been

a source of particles for the continuing coronal hole. Again, if there is a relationship between centers of activity and sequential storms, it is a relationship that develops *after* the region has ceased to be active optically. It is tempting to "see" sequences 1 and 5 as one phenomenon, interrupted in the two rotations 1640 and 1641 by the emergence of a strong family of plages.

Sequence No. 6: The third most active region in 1976, Plage 14352, N19°, ARI = 6, crossed the central meridian on August 8 (Rotation 1644). It returns as Plage 14395, CMP September 4, 1975, ARI =2, N21° and is again one of the 12 most active regions in 1976. Poorly defined Sequence 6 begins on September 2 (Rotation 1645) and recurs at approximately 29 day intervals for perhaps 6 rotations. Did a coronal hole develop on the preceding side of the center of activity mentioned above in its dying stages? It is of interest that the active region possibly associated with this 29-day recurrence pattern in geomagnetic disturbance was at relatively high latitude and included *a new cycle* spot. It is the *only* new cycle center of activity to occur in our efforts to bring active regions in 1976 into possible association with coronal holes and recurrent storms, and it is the only sequence in 1976 with a 29-day recurrence pattern. This was an unexpected possible relationship between the slower rotation rates of high latitude regions and the slower recurrence pattern. It may be only a change coincidence, but it seems worthy of mention.

Sequence No. 7: See discussion of "problem" storm No. 14 on December 16, 1976 in the following section.

In summary, we can write that all of the major sequences in 1976 apparently had at their roots significant centers of activity that could have been near the perimeters of deduced associated coronal holes. The sequential storms occurred as the active regions were dying and continued long after all optical evidence of the active regions had disappeared. If active regions are in any way the source of the particles that stream from the coronal holes, it is something that apparently happens very late in the history of an active center.

In closing, it should be noted that this search for centers of activity possibly related to the sequences of 1976 did not lead directly to an association with the great, old cycle, flaring region of 1976, Plage 14143, CMP March 31, Rotation 1639, ARI = 12. Although this region does not appear at the root of a sequence, it did cross the central meridian 3 days before the continuation of Sequence 4 on April 2. The occurrence of the great

flare-associated geomagnetic storms during this interval may masque possible associations.

D. The "Problem" Storms

The most severe of the six "problem" storms of 1976 (No. 8) began late on December 28, 1976, Rotation 1649. The maximum value of 3-hour Kp for this storm is 6. It is a conspicuous, somewhat isolated, feature on the C9 chart. We know of no appropriate prior flares. It is possible that it is a member of the poorly defined, 29-day recurrent Sequence No. 6. If so, it is not a "problem" storm at all, but is sequential. The same argument applies to storm No. 24 that began on September 1, Rotation 1645. It is possibly the *first* member of the 29-day Sequence No. 6. The "problem" for these storms rests in our uncertainty regarding the validity of the poorly defined, 29-day recurrent Sequence No. 6. We have classified two of the storms in this apparent sequence (nos. 16 and 33) as sequential with a?. Whether these storms should be "sequential" or "problem" is a bit moot.

The same type of uncertainty leads to the "problem" classification of storm Number 14 on December 16, 1976. There were no appropriate prior flares but the storm may be the *first* member of a sequence that exists primarily in 1977. This might be referred to as Sequence No. 7 of 1976 (see Figure 2) and it has one of the twelve most active regions of 1976 (Plage 14553, CMP December 11.5, Rotation 1649, ARI = 3) on the preceding side of the possible coronal hole responsible for the storm of December 16.

The remaining three "problem" storms (No. 18, March 2, Rotation 1638) (No. 22, June 10, Rotation 1642) (No. 23, September 24, Rotation 1646) are all isolated disturbances without suitable prior flares and withour apparent association with sequences. They are the real "problem" storms. However, the maximum 3-hourly Kp was only 5 in each case, so that one can say there were no *severe* truly "problem" storms in 1976. Additionally, we can report that there were no major centers of activity in the neighborhood of potential coronal holes associated with these three storms.

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Dodson, H. W. and E. R. Hedeman, Experimental comprehensive solar flare indices for certain flares, 1970-1974, *Report UAG-52, World Data Center A for Solar-Terrestrial Physics*, NOAA/EDIS (Boulder), 1975.

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TABLE 1

MEASURE OF RESIDUAL SUNSPOT ACTIVITY AT SOLAR "MINIMUM"

(data prepared by M. Waldmeier)

No. of Cycle	Time of Minimum	Smallest Smoothed Monthly Sunspot Relative Number
1	1755.2	8.4
2	1766.5	11.2
3	1775.5	7.2
4	1784.7	9.5
5	1798.3	3.2
6	1810.6	0.0
7	1823.3	0.1
8	1833.9	7.3
9	1843.5	10.5
10	1856.0	3.2
11	1867.2	5.2
12	1878.9	2.2
13	1889.6	5.0
14	1901.7	2.6
15	1913.6	1.5
16	1923.6	5.6
17	1933.8	3.4
18	1944.2	7.7
19	1954.3	3.4
20	1964.7	9.6
21	1976.(3 or 5)	12.2

TABLE 2

COMPREHENSIVE FLARE INDEX FOR "MAJOR" FLARES IN 1976

Date	Start of Flare Observation or Event	Position	Hα Imp.	McMath Plage Number	Event Profile	CFI	Remarks
Jan. 12	0406 UT	S11 E78	Sn	14029	10010	2	II(DKM); IIIg, V (DCM, M, DKM)
Jan. 17	2142	S15 E02	Sf	14029	00110	2	II (DCM, M, DKM), IIIg, V, U(M, DKM)
Jan. 19	1414-II (No flare reported)				00010	1	II (DKM)
Jan. 19	1850-II (No flare patrol)				0-010	1	II(DKM), IIIG, V, U(M, DKM)
Mar. 20	0205-II (No flare reported)				00110	2	II(M,DKM); IIIg, V (DCM, M)
Mar. 20	2257-II (No flare reported)				10020	3	Cont(M,DKM); II (M, DKM)
Mar. 21	0750	N04 W29	1b	14127	31102	7	
Mar. 23	0837 0907	S05 E90	Sb Sn	14143	30234	12	IV (DCM, M)
Mar. 25	1154	S06 E75	Sn	14143	10232	8	IV (DCM, M)
Mar. 25	1305	S05 E69	1n	14143	11231	8	IV (M, DKM)
Mar. 26	1720-IV (No flare reported)				00030	3	IV(M,DKM); IIIg, V(M, DKM)
Mar. 28	0546	S07 E37	Sb	14143	10113	6	II (M)
Mar. 28	0922	S08 E31	Sn	14143	00032	5	IV (DCM, M)
Mar. 28	1342	S06 E37	Sf	14143	00030	3	IV (M, DKM)
Mar. 28	1905	S07 E28	1b	14143	11332	10	IV(DCM, M, DKM); 10 cm G.B.
Mar. 31	1138	S07 W09	1n	14143	11132	8	IV(DCM,M,DKM)
Apr. 05	2152-II & IV (No flare patrol)				0-031	4	IV(DCM,M,DKM); II (M, DKM)
Culgoora Radioheliograph places source at 1.2 $R_{\odot}$ beyond N.E. limb							
Apr. 20	1740	N03 W77	1f	14161	01231	7	IV(M,DKM);II(M,DKM)
Apr. 29	1904	S08 W31	Sn	14179	10131	6	IV (M)
Apr. 30	1242	S06 W41	Sn	14179	10132	7	IV(DCM,M)
Apr. 30	2047	S08 W46	1b	14179	21332	11	IV(DCM,M,DKM); II (M, DKM) 10cm GB
May 01	2149	S08 W60	Sf	14179	10132	7	IV(DCM,M)
May 16	0602	S03 W62	Sn	14203	10110	3	II(M);III G, V (DCM,M,DKM)
Aug. 06	2938-IIN (No flare reported)				00010	1	IIN (DCM,DKM)
Aug. 07	0155	N12 E08	Sn	14352	10212	6	II(M)
Aug. 18	1844	S12 E81	Sb	14375	20113	7	II(DCM,M,DKM)

Table 2 (cont'd)

Date	Start of Flare Observation or Event	Position	Hα Imp.	McMath Plage Number	Event Profile	CFI	Remarks
Aug. 22	1217	S02 W90	Sn	14366	20231	8	IV(DKM)
Sept 01	0650	N19 W57	Sn	14403	00132	6	IV(DCM,M)
Sept 06	0131	N19 W28	Sn	14395	10132	7	IV(M); II(M)
Dec. 09	0201	N03 E33	Sn	14553	00012	3	II(DCM,M)
Dec. 18	2152-II & IV (No flare reported)				00030	3	IV(M);II(M)

Culgoora radioheliograph places source at 1.1 $R_{\odot}$ beyond N.W. limb

TABLE 3A

PRINCIPAL GEOMAGNETIC STORMS IN 1976

Storm Rank	Class of Storm	Time of Start (U. T.)	Dur.	Characteristics Type	Characteristics Deg.	Max. Daily Values Kp	Max. Daily Values Ap	Max. 3-Hour Kp	Sequence Identificatio
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(7)	(8)	(9)
1	Flare-Sequential*	Mar 26 0233	3.5d	Sc	S	55	138	8	Sequence #2
2	Flare (Flare 'a' preferred)	Apr 1 0255	1.4d	Sc	S	46	107	8	—
			This storm is also in a 27 day sequential pattern.						
3	Flare	Mar 2 0800 / 1829	1.5d	g / Sc	S	45	94	8	—
			This storm is also in a 27 day sequential pattern.						
4	Sequential	Jan 10 0621	2.0d	Sc	MS	31	47	7	4
			This storm may be first member of a sequence.						
5	Sequential*	June 30 0251	1.8d	Sc	MS	28	29	7	5
			Storm is first member of well defined sequence.						
6	Flare-Sequential	Sept 19 10-	3.6d	g	MS	41	51	6	5
			This storm is immediately preceded by Storm #13. Together they comprise a sequential storm.						
7	Sequential-Flare	Apr 2 17-	5.8d	g	MS	37	44	6	4
			This storm immediately follows Storm #2.						
8	Problem	Dec 28 2037	2.5d	Sc	MS	36	45	6	(6)
			Storm is possibly a member of 29 day recurrence pattern.						
9	Sequential	Mar 5 21-	7.2d	g	M	36	42	6	4
10	Sequential*	Oct 14 17-	4.0d	g	MS	34	33	6	5
11	Sequential*	Feb 26 22-	3.6d	g	MS	32	34	6	2
12	Sequential-Flare	Aug 23 06-	3.5d	g	MS	31	30	6	5

* Indicates concomitant sector boundary passage.

† See accompanying diagram for schematic presentation of sequential storms.

Table 3A (cont'd)

Storm Rank	Class. of Storm	Time of Start (U. T.)	Dur.	Characteristics Type	Deg.	Max. Daily Values Kp	Ap	Max. 3-Hour Kp	Sequence Identification†
(1)	(2)	(3)	(4)	(5)	(6)	(7)		(8)	(9)
13	Sequential*	Sept 17 20-	1.0d	g	MS	29	33	6	5
			See Storm #6						
14	Problem*	Dec 16 1107	2.0d	Sc	MS	26	28	6	7
			Possibly sequential.						
15	Sequential	July 15 15-	1.4d	g	MS	25	19	6	2
			Last member of a long sequence						
16	Sequential(?)	Oct 30 06-	2.0d	g	M	34	34	5	6
			This storm is possibly a member of a 29-day sequential pattern. See Storm #8.						
17	Sequential*	Nov 10 03-	5.5d	g	M	33	31	5	5
18	Problem	Mar 2 03-	2.1d	g	M	33	32	5	—
19	Sequential	Feb 7 0928	3.6d	Sc	M	32	29	5	4
20	Sequential*	Jan 30 12-	4.5d	g	M	31	29	5	2
21	Sequential*	Feb 17 12-	3.3d	g	M	31	25	5	1
22	Problem	June 10 21-	1.0d	g	M	30	26	5	—
			This is an isolated storm; not in any sequence.						
23	Problem	Sept 24 2345	2.2d	Sc	M	30	24	5	—
			This is an isolated storm; not in any sequence.						
24	Problem	Sept 1 19-	1.0d	g	M	28	32	5	(6)
			Possibly first member of 29-day recurrent sequence. See Storms #8 and #16.						

* Indicates concomitant sector boundary passage.

† See accompanying diagram for schematic presentation of sequential storms.

Table 3 (Cont'd)

Storm Rank	Class. of Storm	Time of Start (U. T.)	Dur.	Characteristics Type	Deg.	Max Daily Values Kp	Ap	Max. 3-Hour Kp	Sequence Identification
(1)	(2)	(3)	(4)	(5)	(6)	(7)		(8)	(9)
25	Sequential*	Jan 20 17- (Jan 21 01-)	4.5d	g	M	28	23	5	1
26	Sequential	Feb 12 15-	2.2d	g	M	28	22	5	3
			Member of weak 27 day sequence.						
27	Sequential	June 17 00-	2.0d	g	M	27	21	5	2
28	Sequential*	June 3 18-	2.3d	g	M	27	20	5	5
			First storm of a sequence.						
29	Sequential*	Dec 7 11-	5.5d	g	M	26	23	5	5
30	Sequential	May 29 19-	1.7d	g	M	26	22	5	4
31	Sequential-Flare*	Apr 21 22-	1.4d	g	M	26	19	5	2
32	Sequential	June 24 1635	1.4d	Sc	M	26	18	5	4
			Last storm of sequence.						
33	Sequential(?)*	Oct 1 08-	1.5d	g	M	25	21	5	6
			This storm is possibly a member of a 29-day sequential pattern. See Storms #8, #16 and #24.						
34	Sequential*	Mar 14 00-	3.0d	g	M	20	14	5	1

* Indicates concomitant sector boundary passage.

† See accompanying diagram for schematic presentation of sequential storms.

TABLE 3B

FLARE AND OTHER SOLAR ASSOCIATIONS WITH GEOMAGNETIC STORMS IN 1976

Storm Rank	Date and Time	Position Lat	Position CMD	McMath Plage Number	Imp.	Profile	CFI	Particle Emission	Δt to Storm
(1)	(2)	(3)		(4)	(5)	(6)	(7)	(8)	(9)
1	Mar 23 0837	S05	E90	14143	Sb	30234	12	—	$2^d\ 18^h$
		Two major flares in same region on March 25 may also be contributors.							
2	(a)Mar 28 1905	S07	E28	14143	1b	11332	10	Protons(40-80MeV) Electrons	$3^d\ 07^h$
	(b)Mar 31 1140	S07	W09	14143	1n	11132	8	Protons in progress	14^h
3	Apr 30 2048	S08	W45	14179	1b	21332	11	GLE PCA	$1^d\ 12^h$
4	No suitable prior flares. Active Region 11029 is beyond east limb.							—	—
5	No suitable prior flares							—	—
6	Sept 17 1805	N20	E82	14429	1n	111(3)2	8?	Low energy protons possible	$1^d\ 16^h$
		Storm possibly associated with this flare is in a sequential storm pattern.							
7	Mar 31 1140	S07	W09	14143	1n	11132	8	Protons in progress	$2^d\ 05^h$
		See Storm #2, Flare (b)							
8	No suitable prior flares. Isolated region 14579 with subflares is on the disk. Storm is in a possible 29-day recurrent pattern. See Storm #16.							—	—
9	No suitable prior flares.								
10	No suitable prior flares								
11	No suitable prior flares								
12	Aug 22 1217	S02	W90	14366	Sn	20231	8	Protons(40-80MeV) Electrons	$0^d\ 18^h$
13	No suitable prior flares							—	—
14	No suitable prior flare. Storm is possibly the first member of a new sequence.							—	—
15	No suitable prior flares.							—	—
16	No suitable prior flares.							—	—
17	No suitable prior flares.							—	—

Table [illegible] (cont'd)

Storm Rank	Date and Time	Position Lat CMD	McMath Plage Number	Imp.	Profile	CFI	Particle Emission	Δt to Storm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
18	No suitable prior flares. An isolated storm between two well defined sequences.						—	—
19	No suitable prior flares.						—	—
20	No suitable prior flares.						—	—
[illegible]	No suitable prior flares.						—	-
22	No suitable prior flares - Region 14259 forms on disk on June 8 with numerous subflares on June 8 and 9.						—	—
23	No suitable prior flares.						—	—
24	No suitable prior flares. Flare on Sept. 1^d 0650 UT (Sn, N19 W57, CFI=6) possibly contributes to Kp max on Sept 2.						—	—
25	No suitable prior flares.						—	—
26	No suitable prior flares.						—	—
27	No suitable prior flares.						—	—
28	No suitable prior flares.						—	—
29	No suitable prior flares.						—	—
30	No suitable prior flares.						—	—
31	Apr 20^d 1740	N03 W77	14161	Sf	00231	6	Protons	1^d 05^h
32	No suitable prior flares.						—	—
33	No suitable prior flares.						—	—
34	No suitable prior flares.						—	—

EXPLANATION OF SYMBOLS AND ABBREVIATIONS USED IN TABLES 3A & B

TABLE 3A

Column

(1) Storm Rank

The storms are ranked according to the general severity of the disturbance. The value of the maximum 3-hourly Kp provided the primary criterion. Maximum daily values of Σ Kp and Ap provide further guidance within the 3-hourly Kp categories.

(2) Storm Classification

This column provides our best judgment regarding the most probable solar cause of the storm under consideration. The terms of the classification are as follows:

FLARE - This classification means that a flare with apparently appropriate characteristics (high value of the Comprehensive Flare Index implying combinations of significant ionizing radiation, Hα importance, or radio frequency emission, especially Type II or Type IV bursts) had been observed within 17^h to $\sim 3^d$ prior to the onset of the storm. A question mark beside the word Flare usually means that ionospheric and radio frequency data indicate that a flare-event has occurred but that an Hα observation of the chromospheric event was not obtained.

FLARE-AMBIGUOUS - This designation indicates that more than one suitable prior flare source is known and that there is no convincing reason for selecting one rather than another as the cause of the storm.

FLARE-SEQUENTIAL - This classification is given when a storm is preceded by an appropriate flare but also occurs in a 27 or ~ 29-day sequence of geomagnetic disturbances. The storm is considered to be primarily flare associated, but the possible presence of "coronal holes" may be influencing the propagation of storm particles.

THE ABOVE THREE CLASSES OF STORMS ALL LEAD TO "FLARE-ASSOCIATED-STORMS"

Column

SEQUENTIAL - This classification is used for storms that occur in ~ 27-day sequential patterns and for which there is no evidence for an appropriate prior flare. In 1976 a poorly defined ~ 29-day sequence also took place.

SEQUENTIAL-FLARE - Storms with this classification are in a sense not uniquely explained. They occur in an apparent sequential pattern but are also preceded by one or more possibly appropriate flares. In our judgment, they seem more like sequential than flare-associated storms.

PROBLEM - This classification is reserved for storms with neither membership in a sequence nor an appropriate prior flare. In our judgment, they represent real geophysical problems. The terms Flare-Sequential and Sequential-Flare have been used by us to designate the other type of "problem" of a multiplicity of possible causes.

An asterisk is included in column (1) when the storm in question began within 1-2 days of the time of an interplanetary sector boundary.

(5) Storm Type

SC = a "sudden commencement" was recorded

g = storm had a gradual beginning

(6) Storm Degree

S = severe

ms = moderately severe

m = moderate

(7)&(8) These columns give maximum values of the familiar indices of geophysical distrubance, ΣKp and Ap as daily values, and the highest value of the 3-hour Kp in the storm.

TABLE 3B

This table provides assorted information relating to solar circumstances thought possibly to be associated with the causation of the geomagnetic storm. In general, it provides data about appropriate prior flares.

Column

(1) Storm Rank

This quantity is given to provide easy comparison with the proper storm in Table 3A to which the solar circumstances refer.

(2) Date and Time of Start of Hα Flare

(6)&(7) Comprehensive Flare Index (CFI): Profile and Index

The Comprehensive Flare Index CFI = A + B + C + D + E, where

A (0-3) = importance of Short Wave Fade or other Sudden Ionospheric Disturbance

B (0-3) = importance of Hα flare

C = characteristic of log of ~ 10cm flux in units of $10^{-22} W(m^2 Hz)^{-1}$

D = dynamic spectrum events: type II = 1, continuum = 2, type IV = 3

E = characteristic of log of ~ 200 MHz flux in units of $10^{-22} W(m^2\text{-}Hz)^{-1}$

The comprehensive flare index ranges from 0 for subflares without significant ionizing or radio frequency emission to 15, 16, and 17 for flares that are outstanding in all aspects of electromagnetic radiation.

TABLE 4

SUMMARY OF CLASSIFICATION OF PRINCIPAL GEOMAGNETIC STORMS IN 1976

Classification	Number
Flare	2
Flare-Sequential	2
Sequential	21
Sequential-Flare	3
Problem	6
TOTAL NUMBER	34

TABLE 5

CHRONOLOGICAL LIST OF PRINCIPAL GEOMAGNETIC STORMS IN 1976

Start	Classification	Rank
Jan 10	Sequential	4
Jan 20	Sequential*	25
Jan 30	Sequential*	20
Feb 7	Sequential	19
Feb 12	Sequential	26
Feb 17	Sequential*	21
Feb 26	Sequential*	11
Mar 2	Problem	18
Mar 5	Sequential	9
Mar 14	Sequential*	34
Mar 26	Flare-Sequential*	1
Apr 1	Flare	2
Apr 2	Sequential-Flare	7
Apr 21	Sequential-Flare*	31
May 2	Flare	3
May 29	Sequential	30
Jun 3	Sequential*	28
Jun 10	Problem	22
Jun 17	Sequential	27
Jun 24	Sequential	32
Jun 30	Sequential*	5
Jul 15	Sequential	15
Aug 23	Sequential-Flare	12
Sep 1	Problem	24
Sep 17	Sequential*	13
Sep 19	Flare-Sequential	6
Sep 24	Problem	23
Oct 1	Sequential(?)*	33
Oct 14	Sequential*	10
Oct 30	Sequential(?)	16
Nov 10	Sequential*	17
Dec 7	Sequential*	29
Dec 16	Problem*	14
Dec 28	Problem	8

* Indicates concomitant sector boundary passage.

FIGURE CAPTIONS

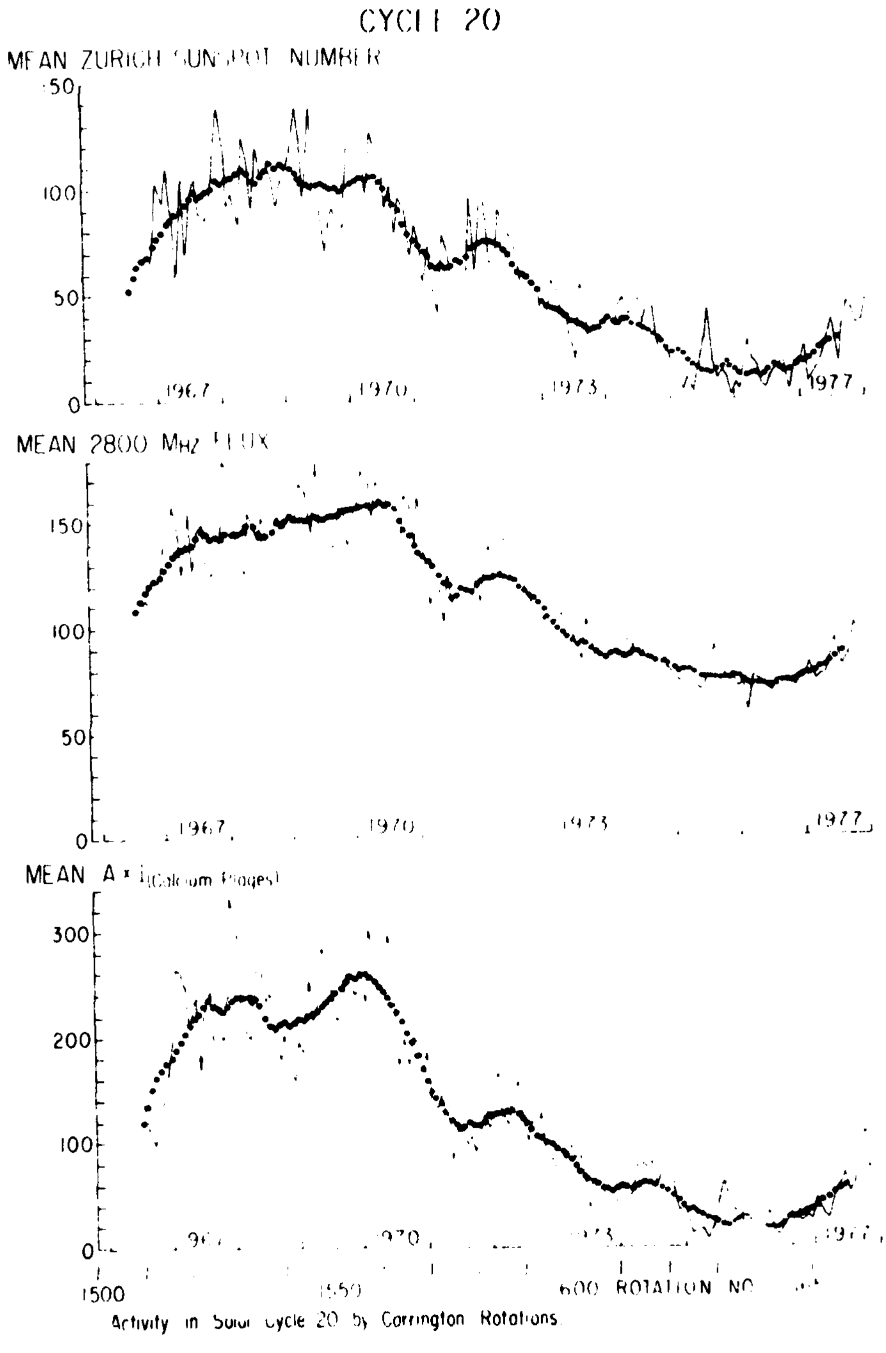
FIGURE 1: Monthly means of sunspot numbers, 2800 MHz radio flux and calcium plage (area x intensity) for the transition between Solar Cycles 20 and 21.

FIGURE 2: Composite plot of times of central meridian passage of active regions on the sun and the occurrence of geomagnetic disturbance at the Earth.

Time intervals are Carrington Rotations. The start of each rotation is indicated by the dates given in the left-hand column. Time increases from left to right. Days and heliographic longitudes in degrees are indicated across the top of the diagram. A portion of each rotation is repeated at the right hand part of the chart.

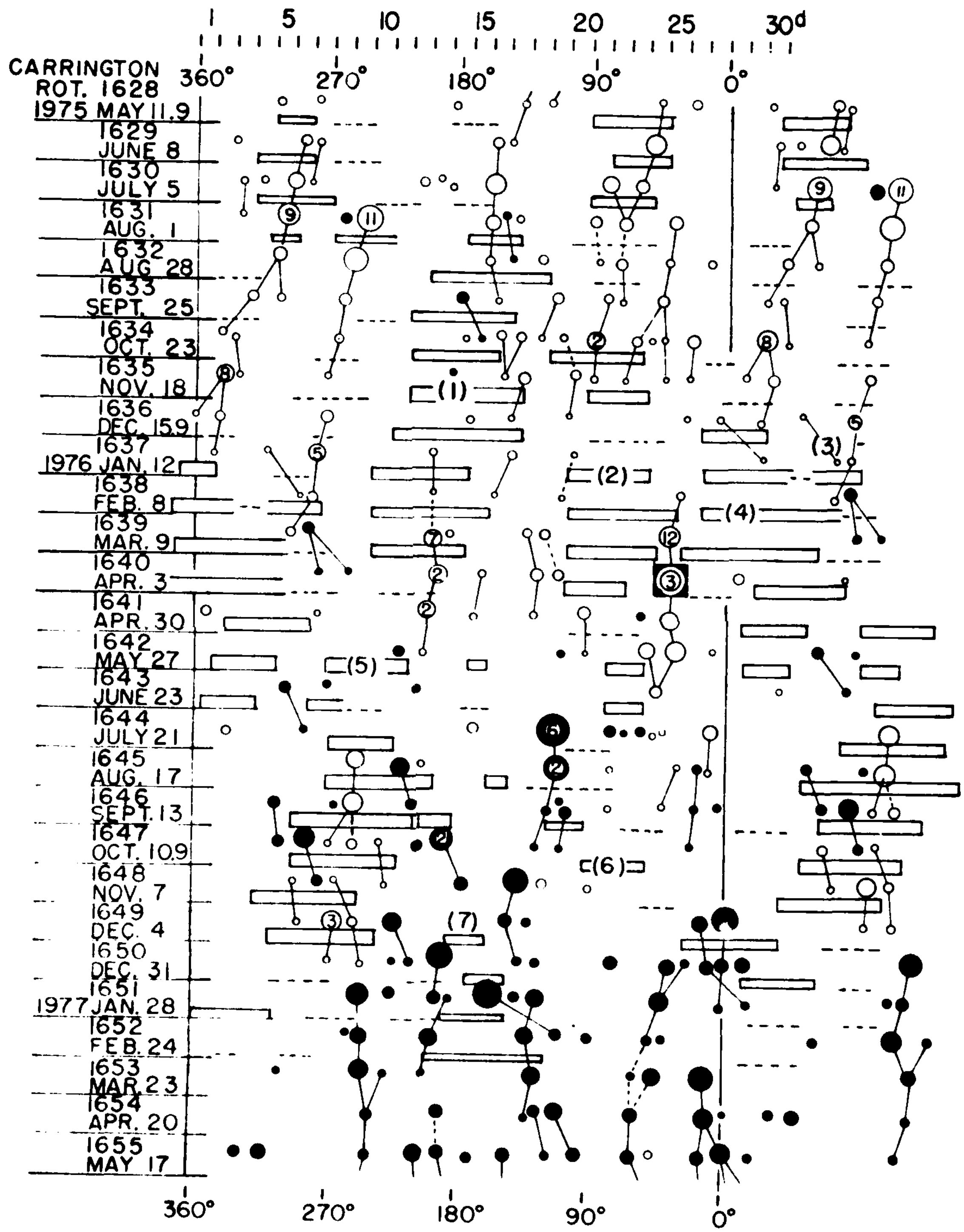
The plages are indicated by circles whose sizes reflect the area and intensity of the region. Successive returns in subsequent rotations are indicated by connecting lines. Old cycle regions are open circles; new cycle regions are filled in. Numbers within circles give the Active Region Indices for "major" regions for the time interval covered by the diagram. Near the end of rotation 1640 the black square surrounding the circle indicates the plage in which a GLE flare occurred.

Intervals of geomagnetic disturbance are represented by horizontal bars if the 3 hourly Kp was ≥ 5, and by dashed lines if Kp was only 4. Numbers in parentheses give the reference number for the sequences referred to in the text.



Activity in Solar Cycle 20 by Carrington Rotations

Figure 1


1
5
10
15
20
25
30d
CARRINGTON
ROT. 1628
360°
270°
180°
90°
0°
1975 MAY 11.9
1629
JUNE 8
1630
JULY 5
1631
AUG. 1
1632
AUG 28
1633
SEPT. 25
1634
OCT. 23
1635
NOV. 18
1636
DEC. 15.9
1637
1976 JAN. 12
1638
FEB. 8
1639
MAR. 9
1640
APR. 3
1641
APR. 30
1642
MAY 27
1643
JUNE 23
1644
JULY 21
1645
AUG. 17
1646
SEPT. 13
1647
OCT. 10.9
1648
NOV. 7
1649
DEC. 4
1650
DEC. 31
1651
1977 JAN. 28
1652
FEB. 24
1653
MAR. 23
1654
APR. 20
1655
MAY 17
(1)
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(3)
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360°
270°
180°
90°
0°

Figure 2

DATE
FILMED

8